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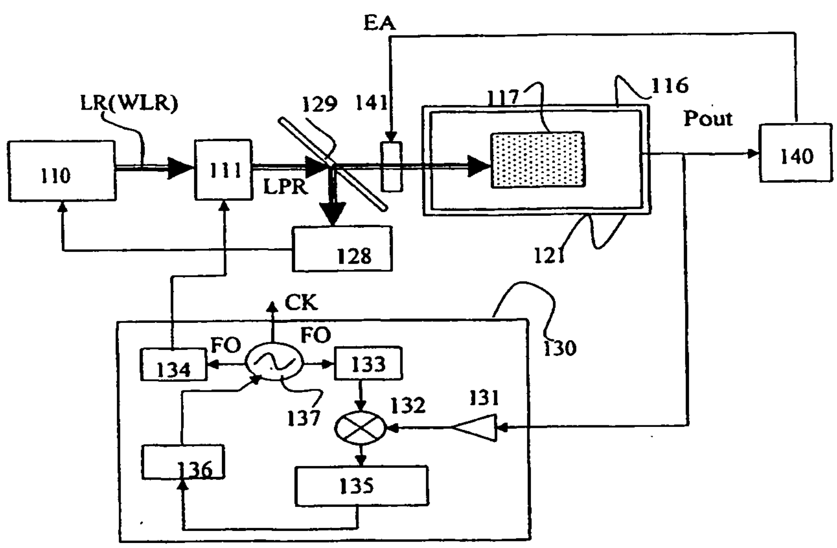
(54) Title: APPARATUS FOR THE GENERATION OF A REFERENCE FREQUENCY



(57) Abstract: Apparatus for generating a reference frequency, comprising means for generating electromagnetic coherent radiation used for exciting two hyperfine atomic levels of a material in order to cause a Coherent Population Trapping phenomenon to occur and to measure the frequency of a radiation emitted by said material in consequence of the excitation, in order to use such frequency as reference frequency. According to the invention, the two hyperfine levels are chosen apt to originate a transition (D_1) in said material, to which transition a symmetrical dipole matrix (DM) is associated, in order to reduce the frequency shift and asymmetries in reference frequency (CK).

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APPARATUS FOR THE GENERATION OF A REFERENCE FREQUENCY

DESCRIPTION

The present invention relates to an apparatus for generating a reference frequency , comprising means for generating electromagnetic coherent radiation used for exciting two hyperfine atomic levels of a material in order to cause a Coherent Population Trapping phenomenon to occur and to measure the frequency of a radiation emitted by said material in consequence of the excitation, in order to use such frequency as reference frequency.

In application in fields like, for instance, laser cooling, magnetometry, laser emissions and, in particular, atomic frequency standards, it is known, in order to obtain a microwave coherent radiation emission, to make use of the phenomenon called Coherent Population Trapping (CPT), that requires, in alkali-metal atoms like cesium or rubidium for instance, to couple two ground states to an excited state, by means of two resonant and mutually coherent radiations.

Said coupling determines coherence effects in the excitation process.

Said coupling is produced, for instance, by coupling two hyperfine levels of the S state of the atom with an excited P levels, by means of two laser radiations with a corresponding frequency.

When the frequency of said radiation resonates with the transitions, a coherence phenomenon occurs, so that the atoms are no longer able to absorb energy from the laser radiations.

Thus, coherence causes a dark line to appear in the atom fluorescence spectrum. So, CPT phenomenon produces the coupling of the two hyperfine levels without influencing their population, that remains in thermal equilibrium. Said coherence originates further an oscillating magnetization that, if the atomic system is placed inside a suitable microwave cavity, , leads to the emission of a coherent microwave radiation, i.e. a maser emission.

The output power is function of the frequency difference between the two CPT stimulating radiations and the maximum power is obtained at the value of the hyperfine frequency.

In figure 1 is shown a basic diagram of an apparatus for generating a reference frequency, making use of the CPT phenomenon, according to the prior art. Further details regarding such an apparatus for generating a reference frequency can be found in the publication "*Coherent population trapping in cesium: dark lines and coherent microwave emission*" di J.Vanier, A. Godone, F. Levi, Physical Review A, vol. 58, n. 3, September 1998, p. 2345-2358, whose contents are here embodied for reference.

Said apparatus comprises a laser 10, emitting a radiation L of wavelenght WL. In figure 2 are shown schematically the energy levels of cesium 133 that are employed. Ground state $6S_{1/2}$ and excited state $6P_{3/2}$ are shown, that are divided by a transition called D_2 transition and corresponding to a 852 nm wavelenght. Ground state $S_{1/2}$ comprises two hyperfine levels corresponding to F=3, and F=4, divide by 9,2 GHz.

The wavelenght WL of radiation L emitted by laser 10 corresponds to the transition from the hyperfine level $6S_{1/2}$ F=3, F=4 to excited state $P_{3/2}$. An electro-optical modulator 11, driven by a synthesis block 12 to a frequency of 4.6 GHz, produces a modulated radiation, that comprises in its spectrum lateral band, spaced in frequency by 9.2 GHz, and necessary for the stimulation, i.e. corresponding to the transition between hyperfine levels $6S_{1/2}$ F=3, $6S_{1/2}$ F=4 shown in figure 2.

In figure 2a the spectrum of the modulated radiation LP is illustated, that shows a carrier J0 at the frequency corresponding to wavelenght WL, and two sidebands J1, i.e. the first harmonics of radiation L. Higher order harmonics J2 are further shown. Sidebands J1, whose amplitude, as it can be observed, is enhanced by the modulation, are at wavelenghts at to stimulate the levels $6S_{1/2}$ F=3, F=4, and originate the CPT phenomenon.

Modulated radiation LP is send, through an attenuator 13, a polarizer 14 and a quarte-wave plate 15,used for obtaining circularly polarized light, to a microwave cavity 16 contininingaa cesium cell 17.

Said cesium cell 17 is a quartz cell containing cesium and a buffer gas, nitrogen for instance, that, as it is known, it is used for decreasing the width of the dark line produced by the CPT phenomenon, due to the Dicke effect.

The atomic system in the cesium cell 17, excited by the modulated radiation LP, generates a microwave field, the detection of which allows for obtaining a clock signal.

The microwave cavity 16, that operates in TE011 mode, is placed in a magnetic field B0, created by a solenoid 25 in order to produce, by Zeeman effect, the separation of the Zeeman sublevels with different quantic number.

Outside the microwave cavity 16 a magnetic shield 21 is provided, in order to have a good uniformity and stability of the magnetic field.

A fluorescence detector 18, placed in a suitable hole 19 of the cavity 16, measures a fluorescence power Pfl, while the output laser radiation LU, to which a transmitted power Ptr is associated, exits from a hole 20.

From the microwave cavity 16 is further taken, through a coupling loop 23, the microwave

output power Pout. that is delivered to an heterodyne receiver 22.

It is possible to use either the coherent microwave emission or the dark line for building an atomic frequency standard.

It is possible. in fact. o obtain that the synthesis block 12, that substantially corresponds to a microwave frequency generator. adnt that in other types of embodiment. can directly drive the injection current of the laser. is locked through phase or frequency modulation techniques to the frequency of the dark line or of the microwave emission.

Since, for instance. the microwave emission frequency. to which the laser driving generator is locked. is taken in correspondence of the maximum of the power, there are some drawbacks regarding applications like atomic frequency standards. because of shifts and asymmetries of the spectrum from which the microwave emission frequency is obtained. and of the dark line in the fluorescence spectrum that is used as a reference.

Such shifts arise because of different factors. depending from magnetic field. from collisions in the buffer gas and. in particular. depending from the laser radiations used to excite the atoms.

It is the object of the present invention to solve the above drawbacks and provide an apparatus for generating a reference frequency. having a more efficient and improved performance with respect to existing solutions.

In this frame. it is the main object of the present invention to provide an apparatus for generating a reference frequency that allows for obtaining a frequency stabilized maser emission and in which the frequency shift and asymmetries due to excitation laser radiation are strongly reduced.

In order to achieve such aims, it is the object of the present invention to provide an apparatus for generating a reference frequency and/or a method for stimulating an apparatus for generating a reference frequency and/or an atomic clock incorporating the features of the annexed claims. which form an integral part of the description herein.

Further objects. features and advantages of the present invention will become apparent from the following detailed description and annexed drawings. which are supplied by way of non limiting example. wherein:

- figure 1 shows a basic diagram of an apparatus for generating a reference frequency according the prior art;
- figure 2 shows a diagram of atomic levels used by the apparatus for generating a reference frequency of figure 1;

- figure 2a shows a basic spectral diagram of a quantity used by the apparatus for generating a reference frequency of figure 1;

- figure 3 shows a diagram of atomic levels used by the apparatus for generating a reference frequency of figure 4;

- figure 4 shows a basic diagram of an apparatus for generating a reference frequency according to the invention.

The invention is based on the observation that frequency shift of the microwave emission and of the dark line, produce by the radiation incident on the cell, are due to power distribution of the laser harmonics, also called sidebands, through two contributions: a first contribution from the frequency shift originated by the power of the laser radiation incident on the cell, independent from the frequency behavior of the laser, and a second frequency shift depending in a quadratic manner from the frequency behavior of the laser.

In rubidium and cesium the line D_2, is part of a spectral lines doublet, that is produced because of the coupling between angular orbital momentum and outer electron spin momentum. The energetic levels doublet is completed by the line D_1.

The interaction between the incident optical radiation and the atom, a cesium atom for instance, is identified by the dipole matrix elements.

According to the invention, in order to produce the CPT phenomenon in the alkali-metal atom, a transition is used that is associated to symmetrical dipole matrix elements, i.e. the transition from line D_1, transition D_1, in substitution of a transition associated to asymmetrical dipole matrix elements, transition D_2, for obtaining to use for the stimulation two laser radiations that are symmetrical with respect to power distribution. In particular this allows for using two sidebands that are symmetrical with respect to power distribution.

In figure 3 transition D_1 e D_2 of the cesium 133 and rubidium 87 are shown. Dipole matrix elements DM are indicated on the side of the lines representing the transitions.. In rubidium 87 case , the line D_2, for instance, that is the transition from ground level F=1 and F=2 to excited level F'=2, bears the value 1/2 and is a symmetrical transition, while transition from level F=1, F=2 to excited level F'=1 is asymmetrical. Because of the small separation in frequency, the two lines are separately excitable. For the transition D_1 , on the other hand, the value of dipole matrix elements DM is respectively $-1/3\sqrt{2}$ and $+1/3\sqrt{2}$, and $-1/2$, $+1/2$, i.e. dipole matrix elements DM are fully symmetrical.

It is observed, further, that for rubidium 87, transition D_1 corresponds to a frequency gap of 6.8 GHz, while 9.2 GHz is the gap for cesium 133.

In figure 4 an apparatus for generating a reference frequency according to the invention is shown.

Said apparatus for generating a reference frequency according to the invention comprises a laser 110, emitting a radiation LR at a wavelenght WLR of 794.98 nm, modulated at a frequency of 6,8/2n GHz, where n=1,2,3, that couples the rubidium 87 levels for the line D_1.

An electro-optical modulator 111 generates a modulated radiation LPR, i.e. generates the sidebands, as the modulator 11 shown in figure 1.

The electro-optical modulator 111 sends said modulated radiation LPR to a beam splitter129, that, besides transmitting the modulated radiation LPR to a cell 117 placed inside a microwave cavity 116, transmits said radiation LPR to frequency lock block 128, that produces a frequency reference to stabilize the laser 110.

The modulated radiation LPR is transmitted, as before said, to the microwave cavity 116, equipped with a magnetic shield 121, that contains a rubidium cell 117, i.e. a quartz cell containing rubidium 87 and a buffer gas mixture.

Microwave output power Pout is taken a transmitted to superheterodyne synthesis block 130, comprising a microwave amplifier 131, receiving power Pout, amplifying it in suitable manner, and transmitting said power Pout then to a mixing block 132 and, from there, to a synchronous detector 135, that detects the frequency corresponding to the peak of the output power Pout and drives, through a servo block 136 a controlled oscillator 137, that operates at a natural frequency of 10 MHz. The output frequency FO of the controlled oscillator 137 is sent to a multiplier 133, that multiplies it by a factor m and sends to the mixing block 132, according the well-known superheterodyne technique.

Further, the output frequency FO of the controlled oscillator 137 is sent, multiplied by a factor n through a multiplier 134, to drive the electro-optical modulator 111. A clock signal CK is taken from the output of the controlled oscillator 137, that is consequently locked to the atomic transition active in the cell 117: said clock signal CJ is the reference frequency supplied by the atomic clock.

Thus, through the superheterodyne synthesis block 130 is generated the driving frequency of the electro-optical modulator 111, so that the modulated radiation is locked to the frequency of the peak of the output power Pout, originated by the maser emission in the cavity 116.

It is possible, of course, to lock to dark line frequency, derived by the fluorescence spectrum, obtained as shown in figure 1, i.e. directly by the spectrum of a sensor analogous to the fluorescence detector 18, that measures a fluorescence power Pfl spectrum. The servo circuit

for obtaining a clock signal from the fluorescence power Pfl will be analogous to the superheterodyne synthesis block 130, that operates with the microwave power Pout.

In figure 4 is further shown an amplitude servo circuit 140, substantially analogous in operation to the superheterodyne synthesis block 130, that controls an amplitude modulator 141, interposed on the path of the modulated radiation LPR. The amplitude servo circuit 140 takes the microwave power Pout and derives an amplitude correction signal EA, used for controlling the amplitude modulator 141.

The control is performed in a similar way as to what proposed for the optical pumping standards, i.e. in J. Camparo, Phys. Rev. Lett. Vol. 80, p. 222, Jan 1998. In other words, the Rabi resonances technique is used. To control the CPT phenomenon that forms the basis of the present invention. It can be demonstrated, indeed, that, in presence of the CPT phenomenon, stimulated in the cell 117, an amplitude modulation of the powr of the laser 110, that is used to excite the transition, generates a resonance at a frequency equal to Rabi frequency in output signal spectrum, i.e. the microwave power Pout. Through the servo circuit 140 a locking to this resonance frequency is performed, in order to stabilize the power of the modulated radiation LPR incident on the cell 117.

From the above description the features of the present invention as well as the relevant advantages thereof are clear.

The apparatus for generating a reference frequency according to the invention advantageously solves the problem of the frequency shift of the maser emission and/or dark line, by using a transition endowed with dipole matrix elements symmetrical. In this way, advantageously, th e power distribution in the harmonics of the spectrum of the modulated radiation used for the simulation can be equal, minimizing the effect of frequency shift due to the amplitude of the modulation used for frequency locking the local oscillator.

Further, being now possible to use excitation radiations with a symmetrical power, a greater compensation of the residual light shift, both for amplitude and power, is also obtained by suitably varying the modulation index, i.e. using a modulation depth such as to eliminate the residual light shift due to all the harmonics, since the principal light shift effect has been eliminated by symmetrizing the sidebands.

The use of rubidium 87 is particularly advantageous since it presents a lower number of Zeeman levels in state associate to D_1 transition, with respect to cesium 133, for istance, so that the levels have a larger population available for the clock transition. Further, advantageously, being the frequency asssociated to D_1 transition of rubidium 87 only 6.8

GHz, this allows for using a larger microwave cavity and obtaining a larger atomic volume in the cell, producing in this way a higher output power and a better signal to noise ratio, that determine a better stability of the frequency reference.

It is obvious that many changes are possible for the man skilled in the art to the apparatus for generating a reference frequency described above by way of example, without departing from the novelty spirit of the innovative idea, and it is also clear that in practical actuation of the invention the components may often differ in form and size from the ones described and be replaced with technical equivalent elements.

By way of example, transitions marked by symmetrical dipole matrix elements can be used, as transition D_1 in cesium 133 or rubidium 85.

CLAIMS

1. Apparatus for generating a reference frequency , comprising means for generating electromagnetic coherent radiation used for exciting two hyperfine atomic levels of a material in order to cause a Coherent Population Trapping phenomenon to occur and to measure the frequency of a radiation emitted by said material in consequence of the excitation. in order to use such frequency as reference frequency. characterized in that the two hyperfine levels are chosen apt to originate a transition (D_1) in said material, to which transition a symmetrical dipole matrix (DM) is associated, in order to reduce the frequency shift and asymmetries in reference frequency (CK).

2. Apparatus for generating a reference frequency according to claim 1, characterized in that said transition is stimulated through the transizione D_1 in alkali-metals..

3. Apparatus for generating a reference frequency according to claim 2, characterized in that means for generating electromagnetic radiation (110, 111) generates excitation modulated laser radiations (LPR), whose sidebands have substantially the same power density.

4. Apparatus for generating a reference frequency according to claim 3, characterized in that the alkali-metal is rubidium 87.

5. Apparatus for generating a reference frequency according to claim 3, characterized characterized in that the alkali-metal is cesium 133.

6. Apparatus for generating a reference frequency according to claim 3, characterized characterized in that the alkali-metal is rubidium 85.

7. Apparatus for generating a reference frequency according to one or more of the preceding claims, characterized in that the cell (117) is contained in a microwave cavity (116) and the mesured frequency of the radiation emitted by the material because of the excitation in order to obtain the reference frequency (CK) is the peak frequency of a microwave coherent radiation (Pout).

8. Apparatus for generating a reference according to one or more of the preceding claims, characterized in that the measured frequency of the radiation emitted by the material following the excitation for obtaining the reference frequency (CK) is obtained by lines of the fluorescence spectrum (Pfl) of the material, in particular of the so-called dark line.

9. Method for stimulating an apparatus for generating a reference frequency, that provides for exciting two hyperfine atomic levels of a material contained in a microwave cavity through laser radiations in order to produce a Coherent Population Trapping type phenomenon and for measuring the frequency of the resulting fluorescence spectrum and/or the frequency of

coherent microwave radiation generated in a microwave cavity characterized by the choosing the two hyperfine levels so that they originate a transition to which a symmetrical dipole matrix is associated in order to reduce the frequency shifts.

10. . Method for stimulating an apparatus for generating a reference frequency , according to the preceding claim. characterized by using the lateral band or harmonics of the laser radiation employed to excite the hyperfine levels that produce a transition to which a symmetrical dipole matrix is associated. and in that said sidebands also have a symmetrical power distribution.

11. Method for stimulating an apparatus for generating a reference frequency , according to the preceding claim. characterized by modulating the laser radiation (LPR) incident on the cell (116) with a modulation depth that eliminates the residual light shift due to the harmonics (J0. J1. J2). after eliminating the main contribution to the light shift by symmetrizing the sidebands (J1).

12. Method for stimulating an apparatus for generating a reference frequency , according to one or more of the preceding claim characterized by using a servo circuit (140) and amplitude modulating means (141) for stabilizing the amplitude of the laser radiation (LPR) incident on the cell (116). said servo circuit (140) operating through the Rabi resonances technique on the output signal spectrum (Pout).

13. Atomic clock characterized by using the apparatus for generating a reference frequency according to claim 1 and/or the method for stimulating an apparatus for generating a reference frequency according to claim 10 to the present description and enclosed drawings.

14. Apparatus for generating a reference frequency and/or method for stimulating an apparatus for generating a reference frequency according to the teachings of the present description and enclosed drawings.

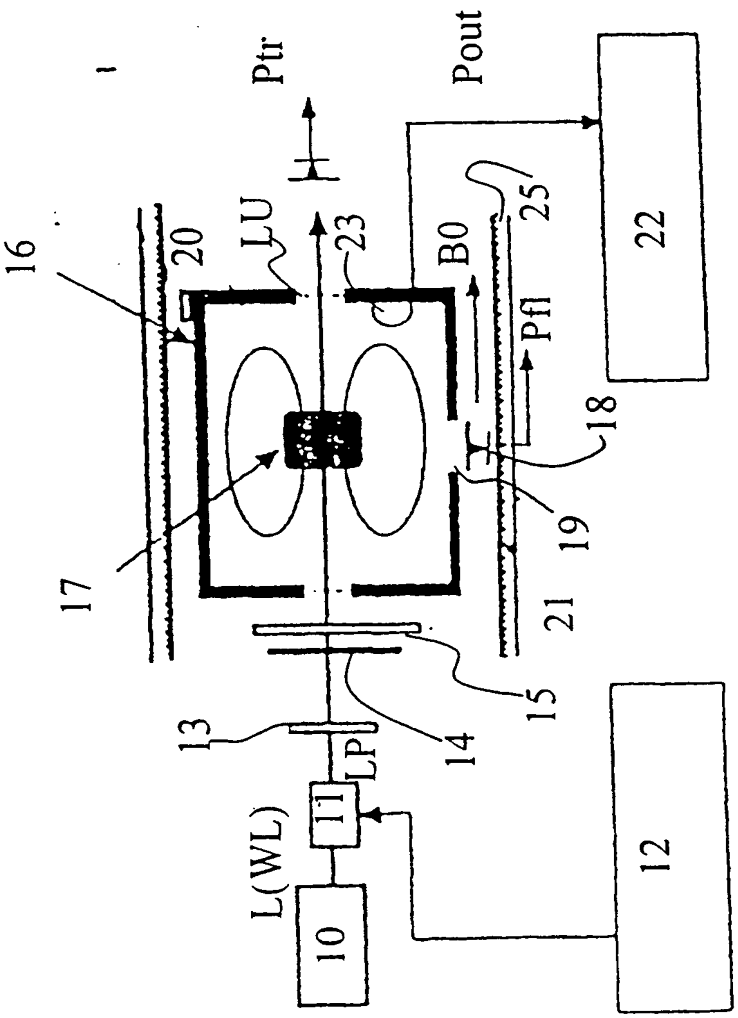


Fig. 1

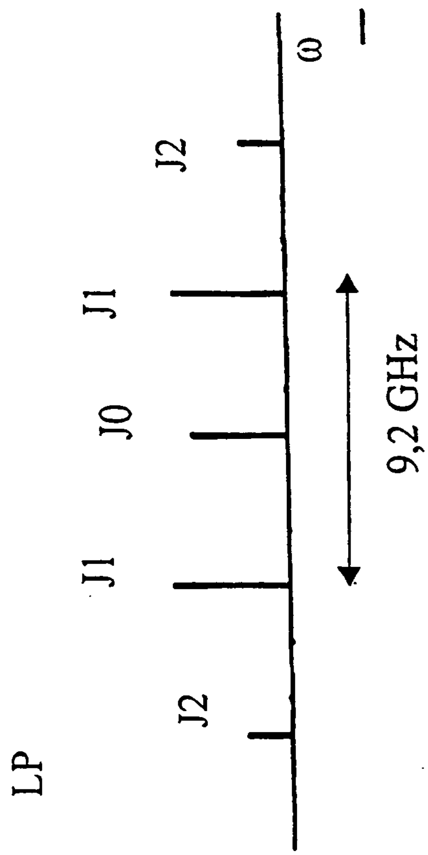
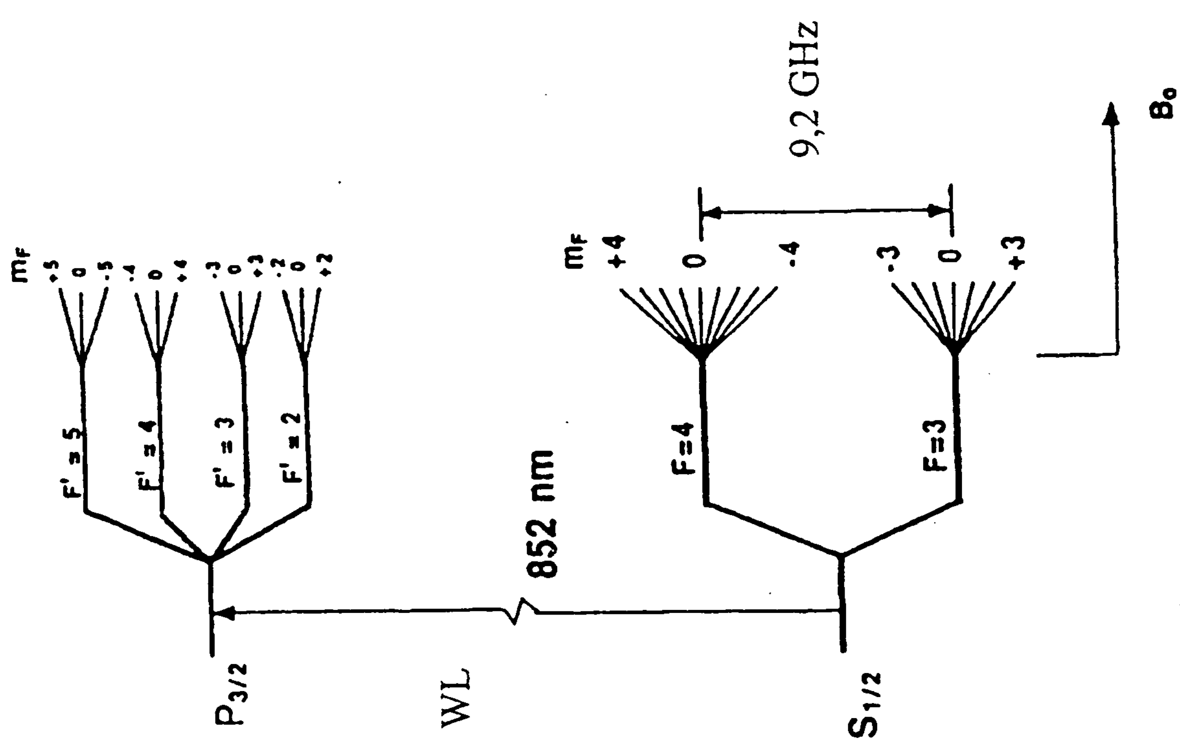

ω
J2
J1
J0
J1
J2
9,2 GHz
LP

Fig. 2a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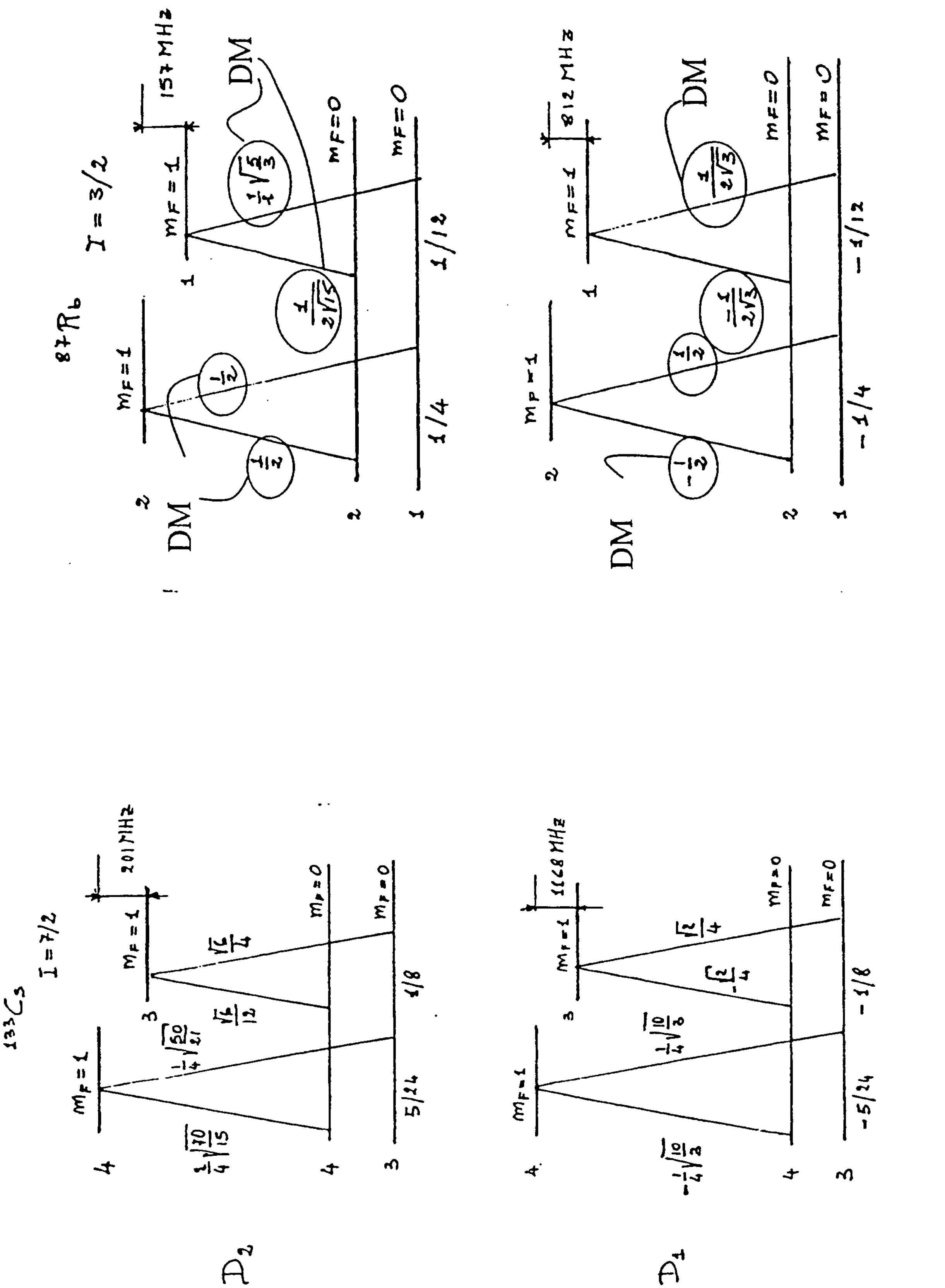
-3
0
+3
9,2 GHz
B_o

Fig. 2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812 MHz
DM
DM
DM
DM
133Cs
I = 7/2
201 MHz
1168 MHz
D2
D1

Fig. 3

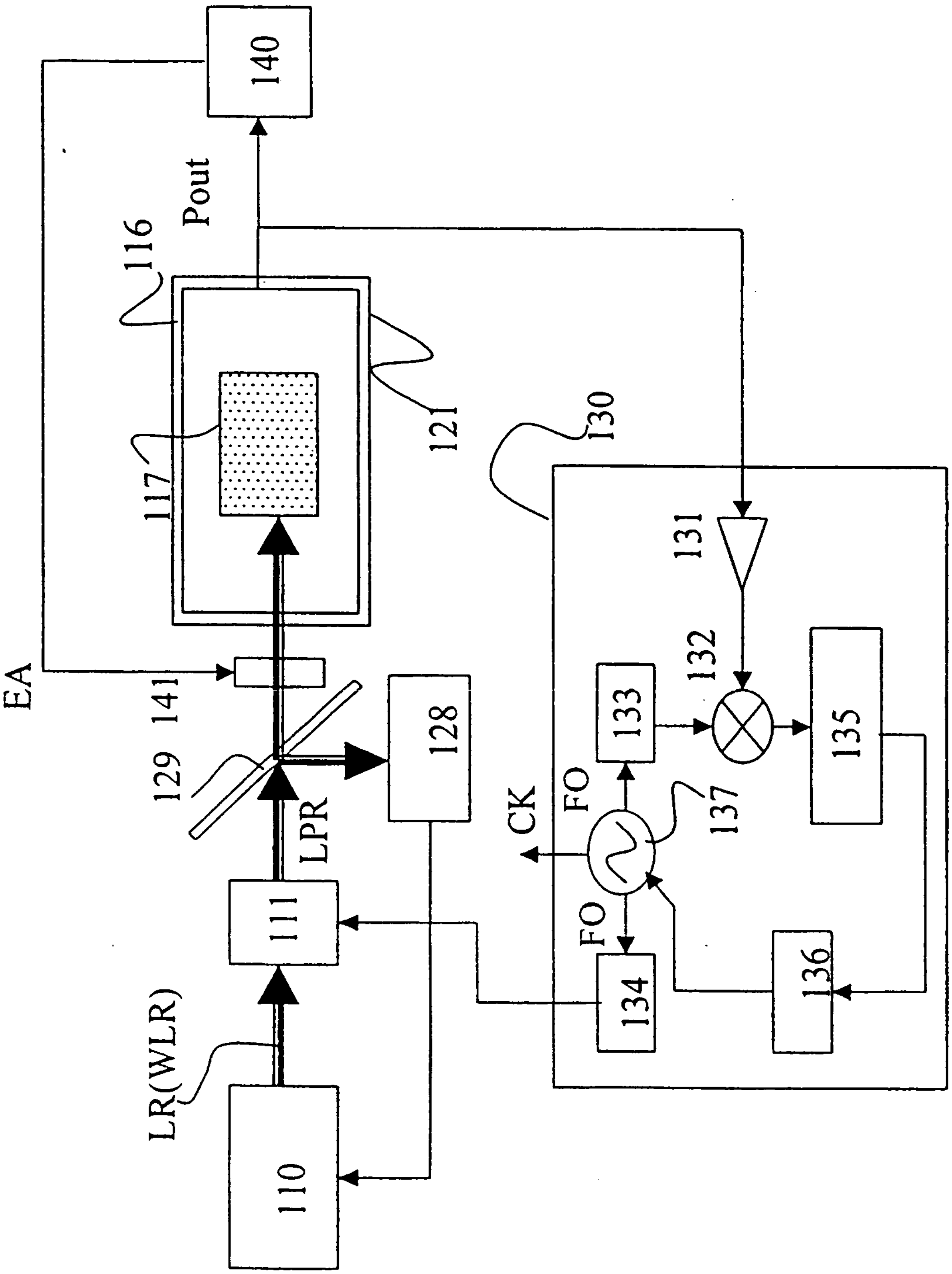
140
Pout
116
117
121
130
EA
141
129
LPR
128
LR(WLR)
110
111
CK
FO
FO
131
132
133
134
135
136
137

Fig. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 00/01411

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H03L7/26

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H03L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X, O	LEVI ET AL.: "The Light Shift Effect in the Coherent Population Trapping Cesium Maser" IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL. NEW YORK, US, 'Online! vol. 47, no. 2, March 2000 (2000-03), pages 466-470, XP002159311 ISSN: 0885-3010 Retrieved from the Internet: <URL:http://iel.ihs.com:80/cgi-bin/iel_cgi?sess=342198686&prod=IEL&page=%2fiel5%2f58%2f17960%2f00827437%2epdf> 'retrieved on 2001-02-01! The Conference was held: 13-16 April 1999 the whole document page 469, column 2, line 9 - line 14 page 469, column 2, paragraph IV	1,2,5,7, 9
P,Y,		4,6,8,13

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[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
2 February 2001	28/02/2001

Name and mailing address of the ISA	Authorized officer
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2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
O	---	
Y	LEVI F ET AL: "CESIUM MICROWAVE EMISSION WITHOUT POPULATION INVERSION" IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS AND FREQUENCY CONTROL, US, IEEE INC. NEW.YORK, vol. 46, no. 3, May 1999 (1999-05), pages 609-615, XP000860585 ISSN: 0885-3010 page 609, column 1, line 12 -page 610, column 1, line 29 page 611, paragraph III page 614, paragraph V figures 1,2,5	4,6,13
A		1,3,5, 7-9

Y	GODONE ET AL.: "A New Atomic Frequency Standard: The coherent Population Trapping Cs Maser" 1998 CONFERENCE ON PRECISION ELECTROMAGNETIC MEASUREMENTS DIGEST, 'Online! 1998, pages 175-176, XP002159308 ISBN: 0-7803-5018-9 Retrieved from the Internet: <URL:http://iel.ihs.com:80/cgi-bin/iel_cgi?sess=349284831&prod=IEL&page=%2fiel4%2f5667%2f15175%2f00699845%2epdf> 'retrieved on 2001-02-02! page 175, column 2, line 25 - line 30; figure 2	8
A		1,3-7,9, 13

A	VANIER J ET AL: "COHERENT POPULATION TRAPPING IN CESIUM: DARK LINES AND COHERENT MICROWAVE EMISSION" PHYSICAL REVIEW, A. GENERAL PHYSICS, AMERICAN INSTITUTE OF PHYSICS. NEW YORK, US, vol. 58, no. 3, September 1998 (1998-09), pages 2345-2358, XP000978042 ISSN: 1050-2947 cited in the application the whole document	1-13

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